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RFID based Efficient Lighting Control

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ABSTRACT

The Kyoto Protocol and the European Energy Performance of Buildings Directive put an onus on governments and organisations to lower carbon footprint in order to contribute towards reducing global warming. A key parameter to be considered in buildings towards energy and cost savings is its indoor lighting that has a major impact on overall energy usage and Carbon Dioxide emissions. Lighting control in buildings using Passive Infrared sensors is a reliable and well established approach; however, the use of only Passive Infrared does not offer much savings towards reducing carbon, energy, and cost. Accurate occupancy monitoring information can greatly affect a building's lighting control strategy towards a *greener* usage. This paper presents an approach for data fusion of Passive Infrared sensors and passive Radio Frequency Identification (RFID) based occupancy monitoring. The idea is to have efficient, need-based, and reliable control of lighting towards a *green* indoor environment, all while considering visual comfort of occupants. The proposed approach provides an estimated 13% electrical energy savings in one open-plan office of a University building in one working day. Practical implementation of RFID gateways provide real-world occupancy profiling data to be fused with Passive Infrared sensing towards analysis and improvement of building lighting usage and control.

1. INTRODUCTION

Facilities Management (FM) is a broad area that covers many different aspects of new, old, and renovated buildings. These aspects range from various types of services in order to improve a building's day-to-day

operation including considerations on efficient use of its energy resources, comfort and reliability, cost savings, and environmental impact. Towards an attempt in achieving these goals, the FM industry is estimated to see a growth of 2-3% by the year 2012 (Shah, 2007) with a current UK market worth of £106.3 billion. Following the Kyoto Protocol set forth in 1997, outlined in (Nations, 2011) that required the European Union to reduce greenhouse-gas emissions by 8% as mentioned in detail in (The Kyoto Protocol, Essence and Goals). Similarly, the UK government has set a target of 60% Carbon Dioxide (CO₂) emissions by 2050 (Sunikka, 2005). This comes forth after an onus placed by the European Energy Performance Building Directive (EPBD) which requires developed countries to set minimum energy requirements for new and renovated buildings (The Kyoto Protocol, Essence and Goals). In order to achieve these goals, the FM industry has over the years adopted modern Information and Communication Technologies (ICT) towards improving strategies and methods of various FM processes. This has been specifically true for efficient automation, control, and monitoring using a Building Energy Management System (BEMS) through the Building Management System (BMS). Although often used interchangeably, a BEMS focuses towards actuation of building components while a BMS provides monitoring of these building components and services.

In order to effectively monitor and manage requirements of building operation, an important parameter to consider is the building occupancy. Because of its dynamic (random and unpredictable) nature, it is very difficult if not impossible to collect accurate, real-time building occupancy data (Sinopoli, 2010). This can result in improper occupancy management, leading to increased total costs (Akbas, Clevenger, & Haymaker, 2007). The task is further made complex if occupant identity and information is required for security purposes. While various methods and techniques have been researched towards efficient occupancy data collection in buildings (Gossauer & Wagner, 2007), they cannot be used for a general application or environment and are only scenario specific. For example, discussing requirements of an occupancy monitoring system, a workspace manager said (Lindkvist & Elmualim, 2010), *“While it is useful to know when people are in the office, it would also be useful to know what areas are used... we would like to know how space is being used”*.

The scope of this research is to evaluate methods and techniques that can influence building lighting control through its occupancy monitoring in specific zones. The main target is to efficiently use building energy for lighting, save the associated cost, and reduce carbon emissions due to the respective lighting usage; all based on a building's occupancy trends. Accurate building occupancy is monitored in real-time through passive Radio

Frequency Identification (RFID) based ‘gateways’. The data collected is envisaged to provide user needs and requirements of lighting conditions for visual comfort throughout a working day. Two parameters are considered to generate occupancy profiling data; 1) *Occupant Density*, which means the number of people present in a zone at any given time, and 2) *Occupancy Pattern* which is a trend of occupant movements and can be considered as a collection of occupant density data over a certain period of time.

This paper is divided into sections in such a way that section 2 provides a brief state-of-the-art of the related work. Section 3 discusses real-world deployment of an RFID-based demonstrator or ‘gateway’ including its working methodology and implementation architecture. Based on the lighting layout and occupancy trends of an open-plan office space, an observational analysis is made in order to find out advantages and feasibility of the proposed methodology in Section 4. Finally, calculations for effective energy and cost reductions through the proposed data fusion method are performed in Section 5, followed by the conclusion in Section 6.

2. STATE-OF-THE-ART

Realizing the importance of occupancy monitoring towards energy savings, the Rensselaer Lighting Research Centre, NY were amongst the first to consider use-patterns of occupants to predict potential energy savings in buildings (Maniccia, 1993). A discussion in ‘*The impact of occupancy profiles on reduction of peak demand and energy use due to lighting controls*’ (Stannard, Keith, & Johnson, 1997) were amongst the next to follow. Effective lighting control in buildings is a function of, and depends upon, the lighting-based activities carried out throughout a working day; also contributing towards the overall carbon footprint which is a measure of the human activities impacting the environment towards climate change. According to (Footprint, 2011), the use of home electricity contributes 12% towards a typical person’s carbon footprint, that too as a primary contribution. Experimental results by (Mahdavi, 2007) monitor user activities aiming to collect useful data towards improved lighting control. In this study, lighting (ON/OFF) and occupancy data (occupied/unoccupied) were collected using IntelliTimer Pro, IT100 data loggers (WattStopper, 2011) by Wattstopper. Amongst different technology uses over the years, Passive Infrared (PIR), ultrasonic, microwave, microphone, and tomographic sensors have been common for general use. This study only considers PIR sensors due to their positive impact and adoption in the commercial market and due to a dominating use in domestic and industrial buildings over the years. These sensors do not emit (hence, passive) but only detect radiations by reacting to infrared heat energy emitted by a human body (Kaushik & Lovell, 2007). A PIR sensor has various switching zones (figure 1) and can be

activated only if and when the detected heat (e.g. human body) moves across two or more zones. Furthermore, many studies such as (Dong & Andrews, 2009) have related building energy savings to occupancy patterns.

Besides considering real-world and actual occupancy monitoring data collected through an implemented system, probabilistic models for occupancy assumptions and predictions have also been used by research studies such as in (Dodier, Henze, Tiller, & Guo, 2006) and (Lopesa, Hokoia, Miuraa, & Shuheib, 2005). For example, Yu et al. in (Yu, Haghighat, Fung, & Yoshino, 2010) proposed a decision tree method for building energy demand modelling based on occupancy. A stochastic occupancy model towards control of building components is presented in (Nicol, 2001). Binomial and Poisson distributions, and Markov Chain processes were used to model building occupancy from multiple sensors in (Hutchins, Ihler, & Smyth, 2007) and (Wang, Federspiel, & Rubinstein, 2005), respectively. Despite these and other literature studies on probabilistic modelling, this paper emphasizes that collection and usage of real-world occupancy data is more accurate and feasible over probabilistically determined data; especially towards validation of a system's working methodology.

Because PIR sensors are line-of-sight devices and cannot 'see' movements around corners, therefore, have limitations in movement detections. Furthermore, requirements to move through two or more switching zones of a sensor suggest large enough bodies or movements which may not always be possible (HCPL, 2011). This is one of the baseline cases for this study, made from field tests in an office environment with limited large body movements. Dead points exist if a sensor is placed in a room of dimensions half the maximum design distance of the sensor, giving rise to false-OFF (Kaushik & Lovell, 2007). A person present in a building zone with no or minimal movements (e.g. typing) may not be picked up by the sensor and it would switch lights OFF (false-OFF) after a certain time. Wave of a hand or body movements are then needed for re-switching to turn lights ON which can be disturbing if occurring frequently. The time for switching OFF lights after no movements is called a PIR sensor's Time Delay (TD) and is typically set between 5 to 30 minutes. Although a sensor TD is adjustable, long TDs can offer less energy savings as, once triggered, the load will remain ON for the respective long TD. On the other hand, a short TD may result in lights switching to a false OFF when no motion is detected while occupants are actually present (Garg & Bansal, 2000). While generally effective in energy savings, occupancy sensors are criticized for energy savings only in off-peak hours. This is mainly attributed to a sensor's TD, for example, a TD of 30 minutes suggests lights to remain ON for 30 minutes even if not needed. Based on these, the main disadvantages of the currently used PIR-only method include;

- A 30 minutes TD is much greater than required, especially when lights can be falsely triggered ON.
- Limitations of PIR visibility causes false OFFs and body movements need to switch lights back ON.
- One PIR sensor controls a number of lights (2-8) via an LCM allowing them all to switch ON/OFF.

Furthermore, as PIR sensors rely on temperature differences of infrared waves when bounced off bodies, they can only detect the presence of a body but have no way of reporting *how many* bodies are present. For these reasons, relying only on PIR sensors for efficient control of lighting based on occupancy monitoring is not recommended in practical situations (Components, 2011). Although overall electrical energy savings are typically calculated to be over 30% (Galasiu & Newsham, 2009) through presence (PIR) sensors in an open-plan office, however, inefficient use and poor installation can rather increase energy consumption instead of reducing it (Floyd, Parker, & Sherwin, 1996). On the other hand, RFID tags overcome these drawbacks and limitations of PIR sensors and can provide individual monitoring and sensing through unique IDs. For this reason, such tags are used for people and inventory monitoring and tracking.

3. EXPERIMENTAL DEPLOYMENT

Besides using and relying only on presence (PIR) sensors, the most common and successful strategy is to combine them with accurate occupant sensing and monitoring information (Judith, Rubinstein, & DiBartolomeo, 2000). The study presented in this paper is an approach to combine the already implemented and available PIR lighting control in a campus building of University College Cork (UCC), Ireland with that of the building's dynamic occupancy information collected through RFID technology. One of the open-plan offices, office 2.12 of UCC's Western Gateway Building (WGB) is considered for implementation of the RFID-based occupancy monitoring demonstrator and analysis for improving building lighting control. Office 2.12 is a 22.94 m × 8.9 m space (figure 2) containing an open area for meetings, semi-private cubical desks for 8 research staff, an open area classroom accommodating 10-15 students on average, and 6 private offices (3 single-occupants and 3 double-occupants). Therefore, a total of 27-32 regular occupants use the office to provide IN/OUT logs that account for occupancy monitoring. The users are provided with off-the-shelf passive UHF inlays (EPC Class 1 Generation 2 compliant) from Alien Technology; these are the ALN-9634 TIE passive RFID inlays (Alien, 2011). The occupancy detection infrastructure 'gateway' is implemented in the office as shown in figure 3. Passive UHF (European 865.6-867.6MHz) RFID technology is deployed using the ISC.LRU2000 fixed RFID reader (OBID, Long-range fixed RFID reader ISC.LRU2000, 2011) by Feig Electronics. The gateway uses four

mono-static OBID i-scan UHF circularly polarized patch antennas (U250/250-EU) (OBID, Circularly polarized antenna, 2011).

The overall system's deployment and working architecture is shown in figure 4. A central data warehouse stores raw (directly from RFID hardware) and custom (External Input) data parameters that are combined for each individual user based on their unique tag IDs. The raw data is passed on after filtering (removing any errors and redundancy in data) from an RFID middleware to a user interface to build profiling data. This data is then available to different stakeholders and system applications over the network or via web services.

3.1. iAnywhere RFID Middleware

The SAP Sybase RFID Anywhere middleware is used to collect bulk amounts of RFID generated data. It is one of the many products under the iAnywhere label (Sybase, 2011). The main advantages of this middleware are that it is open-source and so can be easily integrated for custom programming and use. Its component and services based modular implementation allows easy integration with various RFID hardware; readers, printers, and scanners through their respective .NET software development platforms. Furthermore, it supports web services for data access and availability over the internet using Service Oriented Architecture (SOA).

3.2. Web Services (Service Oriented Architecture, SOA)

From figure 4, the local terminal (host) PC allows access of occupancy data to other applications and users (with access rights) over the internet. One application in a co-partnered research group (Og Murphy & Hadzic, 2011) for example, involves efficient building evacuation planning in emergency and haphazard situations through the availability of real-time occupancy information. Web services implementation was done using a SOA implementation through Google Web Toolkit deployed at a GlassFish Server. (Further discussion of this subtopic would be out of the scope of this paper and is therefore, limited to a brief introduction only).

3.3. Occupancy Calculations

In order to collect occupancy data as people move IN/OUT through office 2.12, the RFID gateway system switches ON and OFF on a daily basis. There are many reasons for this but the foremost is that in order to know whether an individual has entered (IN) or exited (OUT) of the office, the system depends simply on flag statuses, all being initially set to a zero value. From figure 5, every tag-read with an odd value flag status is

considered as an IN while every even value as OUT. For example, an occupant's tag-read while entering the office first time in the morning is assigned a flag value of '1', being odd, it is considered IN. Similarly, if he/she leaves the office, the flag is set to '2', being even, this means an OUT. Although a simple and straight forward approach, but unreliability in tag reading with using passive RFID technology is an obvious disadvantage here. A problem arises when a tag is not read (miss-read). For example, after an odd read, a miss-read will again assign an odd value instead of even and the occupant will be registered as IN instead of OUT (or vice versa). In order to account for this deficiency, the system is validated to determine the accuracy with which tags are read as occupants move IN/OUT about the office. Despite the system's accuracy validation, output of occupancy monitoring is also considered as system validation used towards efficient lighting control.

3.4. System Validation

System's accuracy validation is carried out by comparing actual events (IN/OUT movements of occupants) with those of recorded by the passive RFID gateway. One mode of the Feig RFID reader allows each tag reading or event to be stored as a separate text file with its respective timestamp (date and time) and source ID (antenna number). This allowed easy comparison of entry logs by the RFID gateway with actual events. For actual events, all users were asked to manually fill in timesheets every time they enter/exit the office. These timesheets were displayed on both sides of the door to account for IN and OUT data collection. Occupants were explained the purpose of this task and were ensured data privacy, security, and integrity. After one week's (including weekend) collection of actual data through user timesheets, the results were compared with that of the RFID gateway. The comparison results of one day showed that an overall system accuracy of 91.43% was achieved with an error percentage of 8.57%. This accuracy percentage was found to be quite high and reliable for the RFID system towards occupancy data collection. The error of miss-reads is accounted for due to many reasons such as; the overall working technique of passive RFID based on backscattering, multipath fading and other physical RF phenomena. While people are passing through a gateway may not have the tag at the appropriate angle of orientation for backscattering to take place. Furthermore, placing tags in pockets next to the body or in bags can account for miss-reads. Any miss-reads encountered for IN/OUT events are replaced by an intelligent guess of a reasonable timestamp as every occupant must eventually leave the office every day; another reason why the system is shut down every day and started again every morning with reset (zero initiated) flag values.

4. OBSERVATIONAL ANALYSIS

Although occupancy data was collected for longer periods to build behavioural analyses and predict electrical energy requirements for lighting, data collected for only one day will be discussed. This data is sufficient to explain the concept and provide a case analysis methodology towards potential energy savings. Furthermore, the reason to select only one day's occupancy data result for analysis is that the RFID monitoring system operates on a daily basis from 7:00 to 22:00 hours. The reason for this is due to its dependability on flag values for each tag to calculate IN/OUT (figure 5); this flag value is reset for each tag at system start-up.

From figure 6, a typical trend can be seen with occupants coming into the office in the morning with a decrease during lunch hours; another peak occurs before closing hours, followed by another decrease as people start leaving. Note that as the occupancy trends are recorded on a daily basis, the calculated energy and cost savings results may vary as well. Nonetheless, the methodological approach of how RFID can be combined with PIR sensors to determine occupancy in buildings and empirical methods to determine energy savings are discussed. As mentioned, occupant density and occupancy patterns both account towards occupancy profiling. Profiling provides an estimate of the duration for which individual occupants stay in the office and is considered to be the time at which they use lighting energy. Figure 7 shows individual profiling of the office users over a single day where the straight/flat lines show absentees for the day. This is rather easy and useful data visualization of individuals' movements to determine behavioural trends and office interactions.

4.1. Lighting Layout and Working Description

Office 2.12 has 36 lights, each 2x28 Watts (1 light = 56 W) with the three open areas having 8, 6, and 8 lights, respectively. Two of the six private offices have 3 lights while the remaining four offices have 2 lights each. This layout is shown in the CAD (Computer Aided Design) drawing of the office in figure 2. Table 1 shows the type and total number of lights mounted and total power in watts. The control and operation of these lights for ON/OFF switching is mainly done through presence sensors (PIR) via Lighting Control Modules (LCM), as shown in figure 2. For WGB building offices, the PIR sensors are set at a TD of 30 minutes and any changes in this time period would have to be approved by the building's services and facility managers. This led to one of the main problems towards further implementation of this study as no change was allowed in the building physics or its operation because of it being under continuous use. Therefore, observational analysis is made in order to determine the use of lighting in office 2.12 before and after RFID-based occupancy monitoring. Note that these lights are not dimmable and therefore, preference of luminance levels (LUX) is not considered.

4.2. Proposed Methodology

The currently in place PIR-based lighting control method is termed as *PIR-only* for this paper. Knowing its drawbacks and disadvantages, the proposed method that combines RFID is called the *PIR+RFID* method. Considering the previously discussed limitations and drawbacks of using only PIR sensors, this paper proposes to take advantage of occupant density (IN/OUT) information (figure 6), occupancy profiling (identity) data (figure 7), information of lighting layout and seating position of each occupant. As occupant density and profiling data is provided by the RFID gateway as 'events' occur in real-time, it is proposed to utilize these parameters and have only respective overhead lights switched ON for the relevant user, at specific times, only when required. This can be done as it is now known who occupies what desks at what times from the RFID system's IN/OUT information. Also the TD of PIRs is proposed to be reduced from 30 minutes to 10 minutes. This will ensure obvious savings in energy usage and hence, the associated cost. The proposed methodology is envisaged to be a data fusion system of occupancy monitoring through RFID and PIR-based lighting control. However, the following aspects of potential limitations of the proposed methodology need to be considered;

- To be fully implemented, the proposed system requires changes and modifications in building physics as well as operation of lighting tasks. This can only be allowed from the University's Buildings and Estates Department requiring great amount of documentation to be completed beforehand.
- Occupants may not always remain at their own desks and for any reason may work at other desks or areas. In this scenario, a person's overhead lights need to be switched ON who may not be IN the office; in other words, lights need to be switched ON without the respective RFID tag as 'detected'. A simple remedy to this can be to have a switch at each desk that can override the system's working. In this way without a person being present, their desk-lights can be switched ON/OFF.
- Despite assurance of data integrity, occupants may not feel at ease in having their IN/OUT movements monitored and profiling data built based on the use of RFID-based occupancy monitoring system.

4.3. Observations

It was observed for the specific day of occupancy data presented that a maximum number of 34 out of 36 lights switched ON for different time durations throughout the day, hence, $L_{\max} = 34$. In order to compare the lighting strategy or ON duration of the two methods (PIR-only and PIR+RFID), one criterion considered is the time duration at which the maximum number of lights (L_{\max}) at any given time remain switched ON, i.e. T_{\max} . Similarly, the next criterion considered is the minimum number of lights switched ON (L_{\min}) at any given time

throughout the day. The method with the smallest T_{\max} and L_{\min} will be a better candidate towards efficient lighting control leading to savings in energy (lighting) and the associated cost.

4.3.1. Observations for 'PIR-only' Method

The whole day's lighting duration through the PIR-only method at respective times is given in table 2. From table 2, it can be seen that L_{\max} for the PIR-only method is a time duration of 5 hours and 25 minutes, hence, $T_{\max_PIR}=325$ minutes. The minimum number of lights that remain ON throughout the day is $L_{\min_PIR}=10$.

4.3.2. Observations for 'PIR+RFID' Method

After an observational analysis and calculations for the proposed PIR+RFID method, similar values for lighting durations to be ON is given in table 3. Note again, that the two propositions made for the PIR+RFID method were considered in order to construct this table. Again, these propositions were, 1) to consider only respective lights for relevant users to switch ON using individual tag ID detection and 2) the TD for PIR is reduced from 30 to 10 minutes. From table 3, T_{\max_RFID} (max. lights) can be seen to occur at three different times for a total of $T_{\max_RFID}=295$ minutes (4 hours, 55 minutes). Also, the number of minimum lights switched ON is $L_{\min_RFID}=6$.

5. EFFECTIVE ENERGY AND COST REDUCTIONS

Firstly, an obvious advantage of the PIR+RFID method over PIR-only can be seen in terms of the first criterion, i.e. time duration for the maximum number of lights switched ON. Clearly T_{\max} for PIR+RFID is less than that for PIR-only with a difference of 30 minutes ($325-295=30$ minutes). Secondly, the minimum number of lights switched ON for the PIR+RFID method is smaller than the PIR-only method; with PIR-only, a minimum of 10 lights remain ON for a total duration of 1hr, 30 minutes (first and last row of table 2) throughout the day. On the other hand, with PIR+RFID, only 6 lights remain on for 2 hr (last row of table 3). The overall decreased maximum time (T_{\max}) and less number of lights (L_{\min}) switched ON (also for longer time durations) suggest that the PIR+RFID method translates into better energy utilization for building lighting and relevant cost savings.

As mentioned before, each light is of 56 watts or 0.056 kilowatts (kW). Multiplication of this with the number of lights, say n and time, t (in hours) for which the lights remain ON would give the total energy consumption for time, t in kilowatt hours (kWh). To calculate the cost of energy (electrical), per unit price is considered at a flat rate of €0.1144; which is the charge of one unit of electricity in commercial buildings in Cork (2010).

5.1. Energy and Cost estimations from the two methods

5.1.1. Energy and Cost through 'PIR-only' Method

Based on the values above, the energy in kWh and financial cost for the PIR-only method for ON duration of lights is shown in table 4. From table 4, summation of entries in columns three and four, respectively will give the total energy consumption ($E_{\text{Day_PIR}}$) and total cost ($C_{\text{Day_PIR}}$) of energy for the whole day, respectively. It can be seen that using the *PIR-only* method, the two values turn out to be;

$$E_{\text{Day_PIR}} = 20.0737 \text{ kWh} \quad (1)$$

$$C_{\text{Day_PIR}} = \text{€}2.2964 (\text{\$}3.0915) \quad (2)$$

5.1.2. Energy and Cost through 'PIR+RFID' Method

Similarly, in order to obtain the respective results for the proposed PIR+RFID method, table 5 shows data values for electrical energy consumption and the associated cost. Summation results of the respective columns for the day through the PIR+RFID method are given in equations (3) and (4), respectively;

$$E_{\text{Day_RFID}} = 17.4627 \text{ kWh} \quad (3)$$

$$C_{\text{Day_RFID}} = \text{€}1.9978 (\text{\$}2.6886) \quad (4)$$

5.1.3. Percentage Energy and Cost Savings

By comparing (1) with (3) and (2) with (4) respectively, there are savings in both energy and financial cost of lighting usage through the proposed PIR+RFID method such that;

$$E_{\text{Day_PIR}} - E_{\text{Day_RFID}} = 20.0737 - 17.4627 = 2.611 \text{ kWh} \quad (5)$$

$$C_{\text{Day_PIR}} - C_{\text{Day_RFID}} = 2.2964 - 1.9978 = \text{€}0.2986 (\text{\$}0.4029) \quad (6)$$

Based on the difference in energy consumption by the two methods, the percentage savings can be calculated as;

$$E_{\text{saving}} = \frac{E_{\text{Day_PIR}} - E_{\text{Day_RFID}}}{E_{\text{Day_PIR}}} \times 100\%$$

$$\Rightarrow E_{\text{saving}} = \frac{2.611}{20.0737} \times 100 = 13\%$$

This concludes that an estimated 13% savings in electrical energy is achieved (for the day of data results presented in this paper) through the proposed PIR+RFID data fusion method. Note that this percentage savings

is for one day, i.e. 13 hours (8:30 to 21:30) only from one open-plan office. Also, these hours are more than the normal office hours (9:00 to 17:00) as researchers, and postgrad students work outside these hours on a regular basis. The results for the total number of lights switched ON at hourly intervals for specific durations with respect to the occupancy trend are shown in figure 8. From the comparison of the two methods, it can be seen that the maximum number of lights by PIR+RFID always remains less than the PIR-only method.

5.1.4. Whole Building Energy and Cost Savings Approximation

Because the 13% savings in electrical energy is only for one day and for one office, similar estimations can be related to the whole building's energy usage and savings for a full year. Although this will be an approximation of energy and cost savings, it would give a feasibility idea of a business case to deploy an RFID-based occupancy monitoring system. Calculations can be made assuming similar occupancy trends (figure 6) on a working day for various offices of the building. Out of the complete 365 days of 2010, a total of 251 were working days according to the Irish calendar. Based on this, lighting energy saving estimations for 2010 were;

- One day's energy and cost savings from office 2.12: 2.611 kWh (€0.2986)
- One year's savings from office 2.12: $2.611 \times 251 = 655.361$ kWh ($0.2986 \times 251 = €74.9486$)
- The second floor has 14 similar open-plan offices with almost the same occupancy trends, therefore, energy for this floor: $655.361 \times 14 = 9175.054$ kWh ($74.9486 \times 14 = €1049.28$)
- Assuming similar energy savings for all three floors of the building: $9175.054 \times 3 = 27,525.162$ kWh ($1049.28 \times 3 = €3147.84$)

Therefore, an estimated 27,525.16 kWh energy (electrical) can be saved in one year from the whole building through the use of PIR+RFID method. Again, this is only an approximation as various other factors need to be considered as well, such as the type and use of the space as an office, lab, or lecture hall, the number of regular office users or occupants, environmental conditions and RF propagation predictions from a site survey.

5.1.5. Required Investment and Return On Investment (ROI)

In order to calculate the overall ROI or payback time period, the investment required to deploy RFID gateways throughout the building first needs to be calculated. Each RFID reader installation as a gateway (on a single door) costs approximately €1,000 including all hardware/software components (approximation for passive RFID system components). From the above, as there are 14 facility areas considered; half contain single-door and a

half, a double-door entrance/exit points. Therefore, the RFID deployment required on one floor will be; $(1,000 \times 7) + (2,000 \times 7) = \text{€}21,000$ resulting in a whole-building investment requirement of $\text{€}63,000$ ($21,000 \times 3$). From the above, as each year's total cost savings is $\text{€}3147.84$, the total ROI period required would be $63000/3147.84 = 20$ years. Arguably, these figures of overall investment and ROI period may not seem impressive at first but a few assumptions that were not considered are discussed below;

- With the increase of RFID usage and technology development, devices are expected to drop in prices by almost half. This decrease in prices is due to the increase in the RFID market, (Harrop & Das, 2012) which reports the entire RFID market to increase from \$6.51 billion in 2011 to \$7.67 billion in 2012.
- Like any purchase, a RFID purchase of hardware and software components in bulk amounts would be expect vendor concessions in prices which would further reduce the overall required investment.
- All spaces and the number of facilities considered to calculate the overall cost were considered to have similar occupancy loads and operation timings as in Office 2.12 (figure 6). However, some facilities can have less occupancy loads and shorter operation timings, such as laboratories, seminar halls, etc.
- Finally, the overall ROI should not be considered only in terms of financial cost; the availability of data and its use to facilities manager is a major outcome of this research. One of the main purposes of this research is to provide building facilities managers with real-time occupancy monitoring data in order for them to predict energy use and dependability towards predictive control of building service components.

5.2. Occupant Comfort Considerations

Only having a minimum number of lights switched ON is not the sole target of this study; while aiming for efficient energy use, occupants need to be satisfied towards personal visual comfort. This needs to be in compliance with international standards such as (CIBSE, 2012) for appropriate lux (luminance) level which is 500 lux for demanding tasks (e.g. reading) and 300 lux for less demanding tasks (e.g. meeting) in offices. For this purpose, an average of 302 lux level was measured based on only artificial lighting. Office 2.12 also has North-facing floor-to-ceiling height windows that provide natural day lighting; though being North-facing, availability of natural light depends on the weather and time of the day/year. Moreover, in another study (O'Sullivan, 2011) carried out for the same office, a survey was carried out at three different times (morning, mid-day, and afternoon) of the day through questioning occupants for their visual comfort (Is it too dark or too bright?). From the overall result of the survey, there seems to be a general consensus on the office's visual comfort amongst all occupants. For these reasons, we are not particularly concerned as to when lights switch

ON/OFF, as long as each user has his/her overhead lights ON while at their desk and OFF when they are not at their desk or when not needed.

6. CONCLUSION

In this paper, a new method, the so called *PIR+RFID* was proposed for improved building lighting control for an open-plan office at a University campus building. The method proposes fusion of occupancy monitoring data with that of PIR (Passive Infrared) sensors used to control a building's indoor lighting system. Occupancy monitoring and data collection is done through passive RFID-based 'gateways' installed at the entrance/exit doors of office 2.12. Unique tag ID data is picked up by the gateway to build occupant density information. From the data generated, individual profiling information is available that provides exact information of *who* enters/exits the area at what specific times including the time durations of staying in the office. System validation results show that an accuracy of 91.43% was achieved with the rest being miss-reads that are inserted with appropriate estimated times. This accuracy percentage was good enough for the intended use and application scenario. By exploiting occupancy profiling information, only respective lights are switched ON when needed for individual users based on his/her identity received from the RFID tag ID.

Observational and empirical analysis results show that 2.611 kWh or 13% of electrical energy can be saved in one day (13 hours) from only one office area with 27-32 regular occupants or users. This translates to a total of 655.36 kWh of annual energy and €75 (\$101.18) cost savings from this office only. Likewise, approximate calculation with assumptions of similar occupancy trend shows that a total of 27,525.15 kWh of energy and €3147.84 of cost can be saved for the whole building (with 3 floors and 14 offices on each floor) in one year. This savings in energy translate directly to the amount of coal required to burn at power plants in order to produce electricity. Less or efficient use of energy means less coal burning and Carbon Dioxide release into the atmosphere, leading to reduced contribution towards climate change and global warming, hence, being *green* lights.

The PIR+RFID method shows improvement toward building lighting control with comparison to the currently installed PIR-only method which relies only on PIR sensors. However, a fully practical implementation of the proposed approach in the respective building requires changes in building physics and operation which needs prior approval and consent of various stakeholders including services and facilities managers and the building owner/s. Furthermore, assumptions such as similar occupancy trends throughout the building, same cost of RFID

apparatus, similar operational timings were used to estimate annual energy and cost savings; though in reality, they can be different. With RFID-based occupancy monitoring, granular data visibility is available and can be used for many other applications, e.g. building security and access rights. The proposed method is one of many examples of application uses where RFID has the potential to change building workflows and operations for advantage. With proper site surveys and investments made, the approach presented in this paper provides a clear business case where return on investment is promising financial and environmental benefits.

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TABLES

Table 1: Lighting Distribution and their Power

Type	Quantity	Power (W)	Total Power (W)
A/AE	36	56	2016
L/LE	12	64	768

Table 2: Maximum and Minimum Duration of Lights Switched ON, *PIR-only* Method

Time (24 hr)	No. of lights, N	Duration (min)
8:25 – 9:00	10	35
9:00 – 9:25	18	25
9:25 – 9:50	20	25
9:50 – 10:15	26	15
10:15 – 13:20	30	195 (3hr 15min)
13:20 – 13:45	28	26
13:45 – 19:10	34	325 (5hr 25min)
19:10 – 19:50	28	35
19:50 – 20:15	22	30
20:15 – 21:10	10	55

Table 3: Maximum and Minimum Duration of Lights Switched ON, *PIR+RFID* Method

Time (24 hr)	No. of lights, <i>N</i>	Duration (min)
8:25 – 8:45	10	20
9:00 – 9:25	08	25
9:25 – 9:50	22	25
9:50 – 10:35	28	105 (1hr 45min)
10:35 – 13:20	34	115 (1hr 55min)
13:20 – 13:35	22	15
13:45 – 14:10	26	35
14:10 – 15:35	34	85 (1hr 25min)
15:35 – 15:50	28	15
15:50 – 17:25	34	95 (1hr 35min)
17:25 – 18:25	28	60 (1hr)
18:25 – 18:50	22	25
18:50 – 19:00	18	10
19:00 – 21:00	06	120 (2hr)

Table 4: Energy and Cost of Lighting for one day, *PIR-only* Method

No. of lights, N	Duration (hr)	Energy (kWh)	Cost (€)
10	0.5833	0.3266	0.374
18	0.4167	0.42	0.048
20	0.4167	0.4667	0.0534
26	0.25	0.364	0.0416
30	3.25	5.46	0.6246
28	0.4333	0.6791	0.0777
34	5.4167	10.3134	1.1799
28	0.5833	0.9146	0.1046
22	0.5	0.616	0.0705
10	0.9167	0.5133	0.0587

Table 5: Energy and Cost of Lighting for one day, *PIR+RFID* Method

No. of lights, N	Duration (hr)	Energy (kWh)	Cost (€)
10	0.3333	0.1866	0.0214
08	0.4167	0.1866	0.0214
22	0.4167	0.5134	0.0587
28	1.75	2.744	0.3139
34	1.9167	3.6494	0.4175
22	0.25	0.308	0.0352
26	0.5833	0.8493	1.0972
34	1.4167	2.6974	0.3086
28	0.25	0.392	0.0448
34	1.5833	3.0146	0.3449
28	1	1.568	0.1794
22	0.4167	0.5134	0.0587
18	0.1667	0.168	0.0192
06	2	0.672	0.0769

Table 6: Energy and Cost of Lighting for one day, *PIR+RFID* Method

No. of lights, N	Duration (hr)	Energy (kWh)	Cost (€)
10	0.3333	0.1866	0.0214
08	0.4167	0.1866	0.0214
22	0.4167	0.5134	0.0587
28	1.75	2.744	0.3139
34	1.9167	3.6494	0.4175
22	0.25	0.308	0.0352
26	0.5833	0.8493	1.0972
34	1.4167	2.6974	0.3086
28	0.25	0.392	0.0448
34	1.5833	3.0146	0.3449
28	1	1.568	0.1794
22	0.4167	0.5134	0.0587
18	0.1667	0.168	0.0192
06	2	0.672	0.0769

FIGURE CAPTIONS

Figure 1: Switching zones of a Passive Infrared (PIR) Sensor (Platts, 2004)

Figure 2: Lighting (2x28 watts) layout in Office 2.12 including PIRs and LCM Modules

Figure 3: Implementation of Passive RFID Gateway for Occupancy Monitoring

Figure 4: System Implementation Architecture for passive RFID-based Occupancy Monitoring

Figure 5: Office IN/OUT calculations for occupants

Figure 6: Hourly trend of Occupant Density over one day in Office 2.12

Figure 7: Hourly trend of Occupancy Profiling over one day in Office 2.12

Figure 8: *PIR-only* vs. *PIR+RFID* Methods of Lighting Control based on Maximum Occupancy

FIGURES







